Damage propagation in corroded reinforcing bars with the effect of inelastic buckling under low-cycle fatigue loading

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ABSTRACT: The effect of inelastic buckling on low-cycle high amplitude fatigue life of reinforcing bars is investigated experimentally. The results show that the inelastic buckling, bar diameter and surface condition are the main parameters affecting the low-cycle fatigue life of reinforcing bars. Through nonlinear regression analyses of the experimental data a new set of empirical equations for fatigue life prediction of reinforcing bars as a function of the buckling length and yield strength are developed. Finally, these empirical models have been implemented into a new phenomenological hysteretic material model for reinforcing bars. Furthermore, the combined effect of inelastic buckling and chloride induced corrosion damage on low-cycle high amplitude fatigue life of embedded reinforcing bars is investigated experimentally. The low-cycle fatigue tests on corroded reinforcing bars varied in percentage mass loss, strain amplitudes and buckling lengths are conducted. The failure modes and crack propagation are investigated by fractography of fracture surfaces using scanning electron microscope.

1 INTRODUCTION

Corrosion of reinforcing steel is the most significant structural deficiencies in aging bridges located in chloride laden environment. Many of these bridges are also located in regions with high seismic activities. These structures experience dynamic/cyclic loading due to earthquake over their service life. Furthermore, the current design approach allows reinforced concrete (RC) structures dissipate energy during large earthquake events by occurring plastic hinges in beams and columns. The inelastic cyclic deformation in plastic hinge regions during large earthquakes results in a significant tension and compression strain reversals. Among RC components, bridges piers are the most vulnerable components in earthquake due to the simple structural system of bridges. Moreover, there is a large number of existing bridges around the world that were designed prior to the modern seismic design codes and therefore they are not properly detailed for seismic loading. These aging structures are also suffering from long-term material deterioration.

The current performance-based seismic design philosophy of reinforced concrete (RC) structures relies on the proper detailing of plastic hinge regions where most of the inelastic deformations are expected to occur. The inelastic cyclic deformation in plastic hinge regions results in a significant tension and compression strain reversals. Among RC concrete components, RC bridges piers are the most vulnerable components. This is because the structural system of bridges is very simple (a single degree of freedom system). Unlike buildings where plastic hinges are designed to occur in beams, due to the nature of the structural system of bridges the plastic hinges are forced to occur in piers. As a result, they should be able to accommodate a significant inelastic deformation due to earthquake loading.

Meda et al. (2014), Ou et al. (2011) & Ma et al. (2012) have investigated the effect of corrosion on the nonlinear response of RC beams and columns subject to cyclic loading experimentally. The results from these experimental studies show that non-uniform pitting corrosion affects the global response of corroded RC elements subject to cyclic loading. This is mainly due to the influence of corrosion on premature buckling and low-cycle fatigue life of corroded bars.

The low-cycle fatigue life of uncorroded reinforcing bars without the effect of buckling has been studied by other researchers (Mander et al. 1994, Chang & Mander 1994, Brown & Kunnath 2004, Higai et al. 2006, Hawileh et al. 2010). Kashani et al. (2015a) studied the effect of inelastic buckling on low-cycle fatigue life of uncorroded reinforcing bars experimentally. Apostolopoulos (2007) and Hawileh et al. (2011) investigated the effect of corrosion on low-cycle fatigue life of reinforcing bars without the effect of buckling. More recently, Kashani et al. (2013a,b,c) investigated the impact of pitting corrosion on inelastic buckling and nonlinear cyclic response of reinforcing bars experimentally.

This paper summarises the results of the experimental study conducted by Kashani et al. (2015a,b). It reports the combined effect of corrosion damage and inelastic buckling on low-cycle fatigue life of reinforcing bars experimentally. The effect of buckling and corrosion on the total hysteretic energy dissipation capacity and the number of cycles to failure are investigated. Using scanning electron microscope the fractography of fracture surfaces is studied. The experimental results show that the low-cycle fatigue life of corroded reinforcing bars with the effect of inelastic buckling is greatly influenced by loading history and therefore, has a significant path dependency.

2 EXPERIMENTAL PROGRAMME

2.1 *Accelerated corrosion procedure*

In order to realistically simulate the corrosion of steel reinforcement embedded in concrete a total of four reinforced concrete specimens were cast. Each specimen dimensioned 250×250×700mm incorporated 12 number 12mm diameter B500 reinforcing bars. The concrete mix was designed to have a mean compressive strength of 30MPa at 28 days with a maximum aggregate size of 12mm. The specimens were cast with a nominal cover of 25mm. An accelerated corrosion procedure was used to simulate long term corrosion. After corrosion simulation, the concrete specimens were broken open and the corroded bars were carefully removed from the concrete. To ensure that the concrete was completely removed from the corroded bars, a mechanical cleaning process using a bristle brush was used, in accordance with ASTM G1-03 (2011).

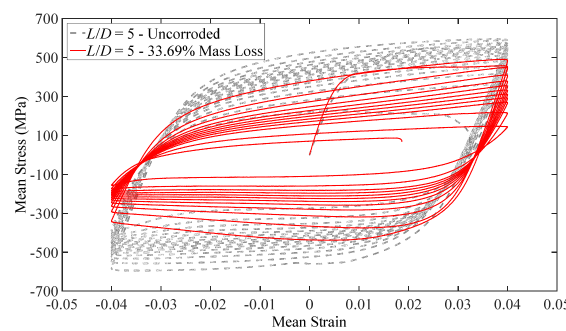
2.2 *Low-cycle high-amplitude fatigue test*

This part of the experiment had two parts. The first part was to explore the impact of inelastic buckling on low-cycle fatigue behaviour of reinforcing bars and the second part was to explore how corrosion damage influences the low-cycle fatigue behaviour of reinforcing bars with the effect of inelastic buckling. The focus of this paper is to summarise the experimental results of the second part related to corroded bars. Further details of the first part is available in Kashani et al. (2015a).

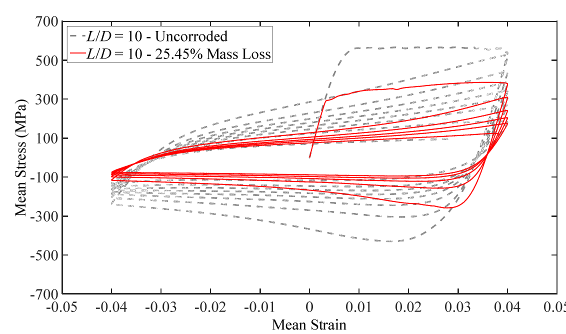
A total of forty eight low-cycle fatigue tests are conducted on corroded reinforcing bars with different buckling lengths and strain amplitudes. The slenderness ratio is defined by the L/D ratio where L is the length and D is the bar diameter. The L/D ratios tested in this experiment are 5, 10 and 15. The total strain amplitudes used in the low-cycle fatigue tests are 1%, 2%, 3%, 4% and 5%.

3 INFLUENCE OF BUCKLING AND CORROSION ON CYCLIC STRESS-STRAIN RESPOSNE OF REINFROICNG BARS

Figure 1 shows hysteretic loops of corroded bars with different L/D ratios and percentage mass losses under 4% strain amplitude fatigue test. It should be noted that, throughout this paper, the stress of corroded bars is calculated considering a uniform volumetric mass loss (mean stress) and the strain is the average strain over the length (L) of the bars (mean strain). Figure 1(a) shows that hysteretic response of the uncorroded bars with L/D = 5 are almost symmetrical in tension and compression. However, as the slenderness ratio of bars increases a pinching response is observed which is due to the impact of inelastic buckling and geometrical nonlinearity on the hysteretic response. The results show that the fatigue induced crack initiation in the group of bars with L/D = 10 and 15 is much quicker than the group of bars with L/D = 5. Previous research has confirmed that buckling is not an issue in reinforcing bars with L/D < 6 (Kashani et al. 2013a,b). However, once reinforcing bars start corroding the nonuniform corrosion over the length of corroded bars changes the effective slenderness ratio (L/D) of these bars. Therefore, inelastic buckling affects the stress-strain response of these bars as shown in Figure 1(a). The strain amplitude is the most important parameter affecting the low-cycle fatigue of materials. The experimental results show that the influence of strain amplitude increases by increasing the L/D ratios of bars.



(a)



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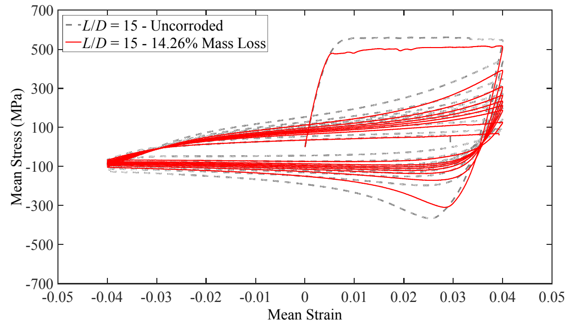


(c)

Figure 1. Impact of corrosion on cyclic stress-strain response of reinforcing bars: (a) L/D = 5 (b) L/D = 10 (c) L/D = 15

4 INFLUENCE OF BUCKLING AND CORROSION ON HYSTERETIC ENERGY DISSIPATION

The total dissipated energy to failure is one of the important low-cycle fatigue parameter that needs to be evaluated. This is a good representation of the energy storage capacity of the material during seismic event. Figure 2 shows the normalised total hysteretic energy of uncorroded bars varied in slenderness ratios and strain amplitudes. The variable E_t is the total hysteretic energy of bars in low-cycle fatigue test and E_y is the elastic energy of the corresponding bars under monotonic tension. As it is shown in Figure 2, buckling has a more significant impact on energy dissipation at lower strain amplitude. As the strain amplitude increases beyond 2.5% almost all of the bars with $L/D \geq 8$ converge towards the same point.

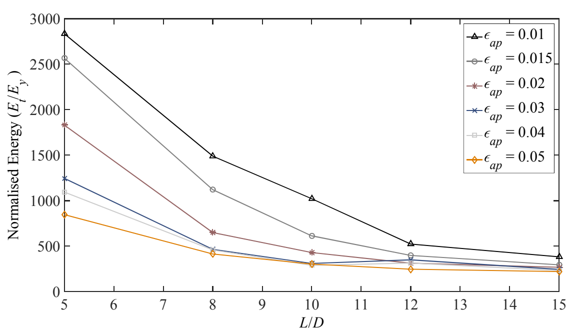
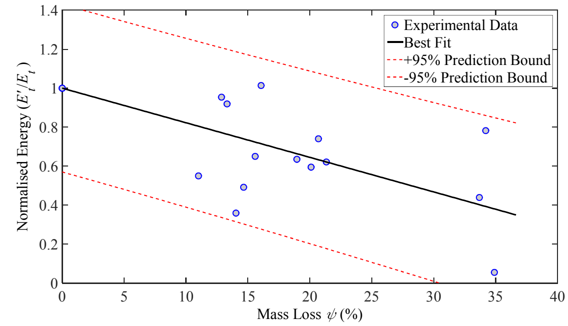
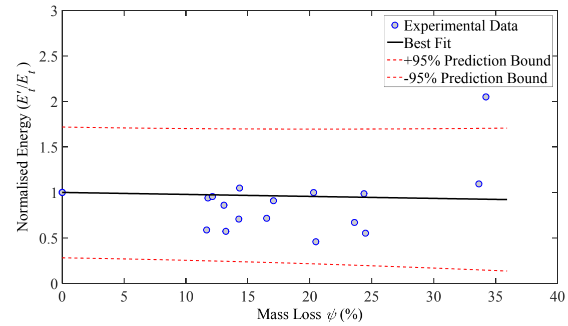


Figure 2. Normalised dissipated hysteretic energy of uncorroded bars

Figure 3 shows the impact of corrosion on normalised dissipated energy of corroded test specimens. Figure 3 shows that corrosion has a more significant impact on energy dissipation capacity of bars with L/D = 5. Figure 3 suggests that increasing the L/D ratio of test specimens reduces the impact of corrosion on energy dissipation capacity of corroded bars under constant amplitude fatigue test.



(a)

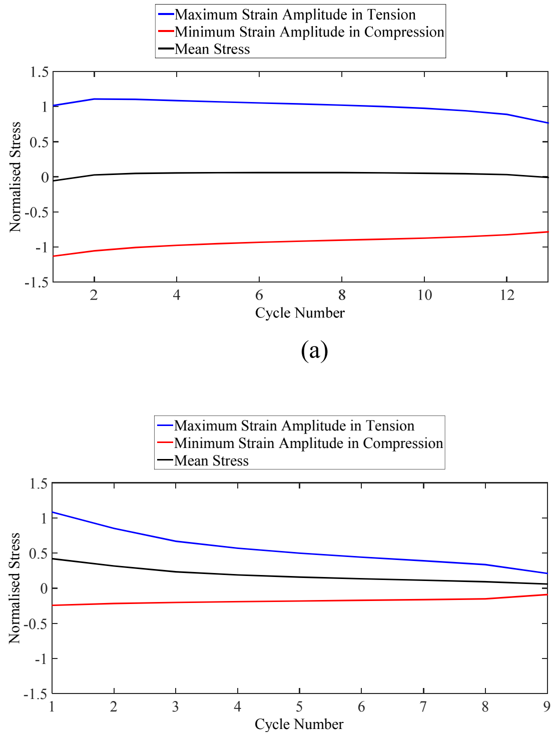


(b)

Figure 3. Impact of corrosion on total hysteretic energy dissipation of reinforcing bars: (a) L/D = 5 and (b) L/D = 15

5 INFLUENCE OF BUCKLING AND CORROSION ON THE NUMBER OF CYCLES TO FAILURE

Figure 4 shows example graphs of the cyclic stress loss of 16mm diameter bars under low-cycle fatigue test with 4% strain amplitude. It should be noted that the normalised stress in Figure 4 is the value of the stress at the pick strain amplitude in tension and compression in each half cycle normalised to the yield stress. Figure 4(a) shows that the stress loss in tension and compression is almost symmetrical for bars with L/D = 5. Given a zero mean strain history is used in the experiment, as expected, the mean stress loss is almost zero in bars with L/D = 5. However, as it is shown in Figure 4(b) the normalised stress loss in tension and compression is not symmetrical for bars with L/D = 15. This results in moving the normalised mean stress graph from zero. This indicates that buckling increases the stress loss of reinforcing bars in compression under cycling loading. Moreover, Figure 4(b) shows that the stress loss in tension much faster than bars with L/D =5



(a)

(b)

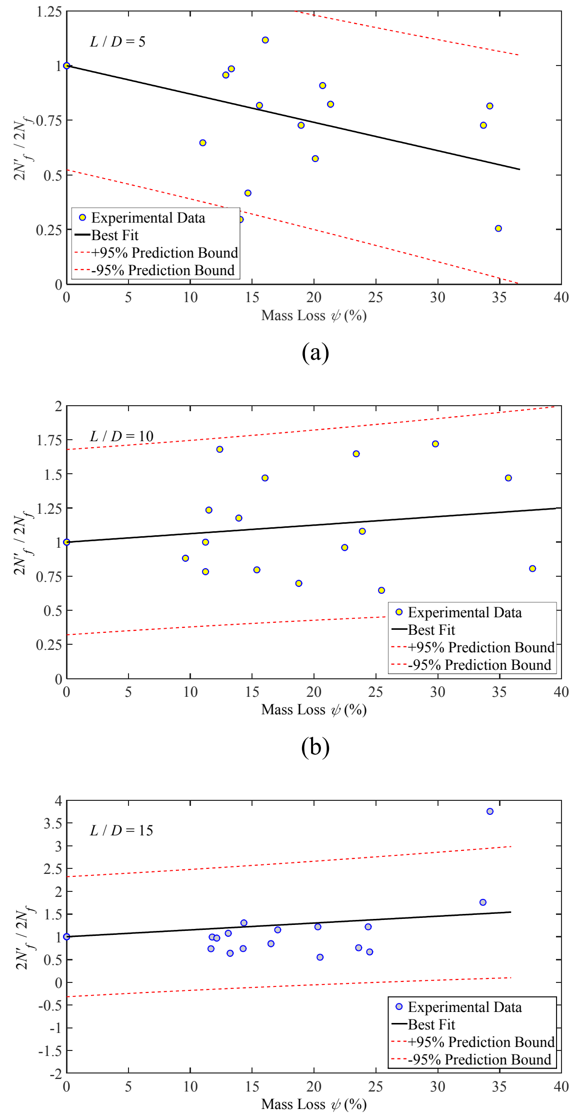
Figure 4. Stress degradation of 16mm ribbed bars: (a) *L*/*D* = 5, 4% strain amplitude (b) *L*/*D* = 15, 4% strain amplitude

The Coffin-Manson (1965) model is one of the most popular methods among researchers as they are easy to be used implemented in nonlinear material models (Kashani et al. 2015c) of finite element packages for seismic analysis of civil engineering structures such as OpenSees (2014). The Coffin-Manson equation uses the strain life approach to model the low-cycle fatigue life of engineering materials. The plastic strain amplitude is the most important parameter affecting the low-cycle fatigue life of material. Therefore, Coffin-Manson model, as described in Eq. (1), relates the plastic strain amplitude (ε_p) to the fatigue life.

$$\varepsilon_p = \varepsilon'_f \left(2N_f\right)^c \tag{1}$$

where, ε'_f is the ductility coefficient i.e. the plastic fracture strain for a single load reversal, c is the ductility exponent and $2N_f$ is the number of half-cycles (load reversals) to failure. This section investigates the influence of corrosion on the number of half-cycles to failure ($2N_f$).

As expected, the degree of corrosion damage has a significant impact on the number of half-cycles to failure. The number of half-cycles to failure for each corroded specimen ($2N'_f$) is normalised to their corresponding uncorroded specimen ($2N_f$) and plotted versus percentage mass loss in Figure 5. The best linear fit to the experimental data in Figure 5 shows that corrosion significantly reduces the number of half-cycles to failure for specimens with *L*/*D* = 5. However, it shows that corrosion increases the number of half-cycles to failure for specimens with *L*/*D* = 10 and 15.



(a)

(b)

(c)

Figure 5. Impact of corrosion on number of half-cycles to failure: (a) *L*/*D* = 5, (b) *L*/*D* = 10 and (c) *L*/*D* = 15

Figure 7 shows the impact of corrosion on cyclic stress loss of reinforcing bars. It should be noted that the calculated stress in Figure 7is based on the average reduced area of corroded bars and is normalised to the yield stress of uncorroded specimen. Figure 7 shows that as the corrosion damage increases in group of bars with *L*/*D* = 5, the number of cycles to failure decreases and cyclic stress degradation increases. Figure 7 shows that (as expected) as the corrosion damage increases the normalised stress decreases which suggests that the corroded bars in Figure 7 have irregular distribution of corrosion along the length of the bars.

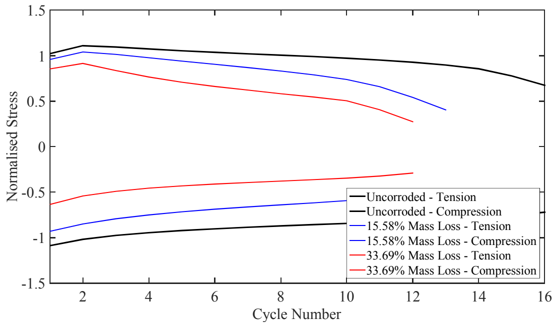
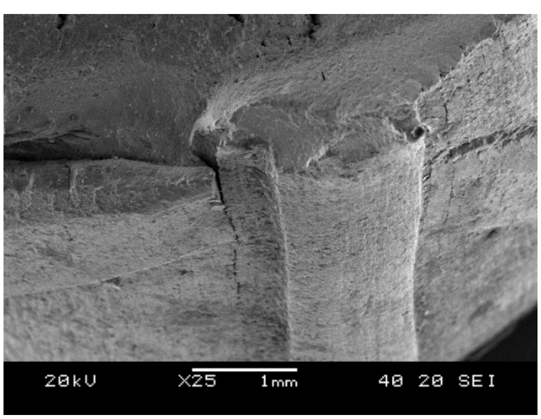


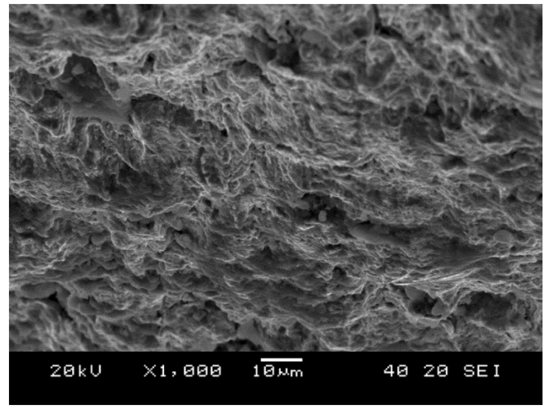
Figure 6. Impact of corrosion on cyclic stress loss of reinforcing bars at 4% strain amplitude with $L/D = 5$

6 FRACTOGRAPHY OF THE FAILURED SURFACES USING SEM TECHNIQUE

Scanning Electron Microscope (SEM) was used for fractography of the fractured surfaces. This was used to take detailed images of some sample fractured specimens to investigate the crack propagation by topography of the fractured surface. This apparatus focusses a beam of high energy electrons on to the specimens that interact with the atoms at the surface to produce a detailed scan of the specimen. It was observed that the fatigue crack of the uncorroded ribbed bars under repeated cyclic loading initiated along the root of the transverse rib on the inside face of the buckled bar. After initiation, the cracks propagated away from the transverse rib on the bar surface into the body of the bar normal to the bar axis. This suggests that the largest stresses lie in the longitudinal direction, as otherwise the cracks would have grown along the along the root where the magnitudes of stress concentrations are much higher than elsewhere. Figure 7 shows the fractographs of uncorroded bars with $L/D = 15$. The light areas shown in Figure 7 indicates a sudden fracture near the rib root.



(a)

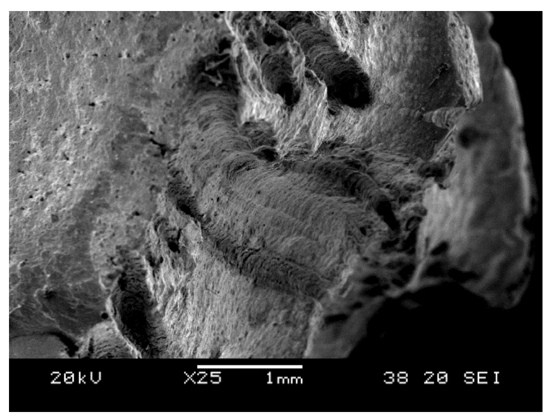


(b)

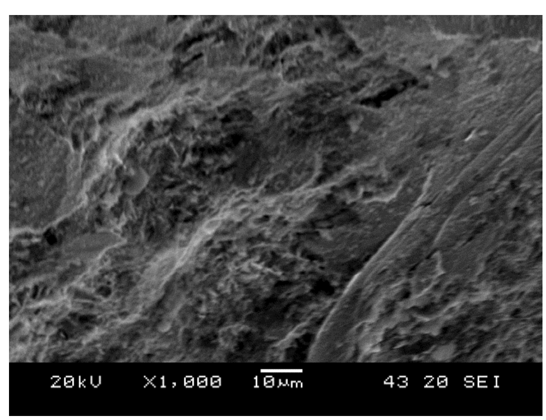
Figure 7. SEM fractographs of fractured uncorroded bars with $L/D = 15$ after low cycle fatigue tests at 4% strain amplitude

In corroded bars the location of crack initiation is significantly affected by the distribution of corrosion pits along the length of the bars.

Figure 8 shows example fractographs of corroded bars. Comparing Figure 8 (a) and (b) with Figure 8 (c) and (d) shows that the rough and light areas are associated with brittle and sudden fracture in this corroded bar with $L/D = 5$. It also shows that corrosion resulted in some porosity around the surface of corroded bar which has a significant impact on crack initiation and the number of cycles to failure. It is also evident that corrosion induced porosity around the surface of corroded bars has a significant impact on the number of cycles to failure.



(a)



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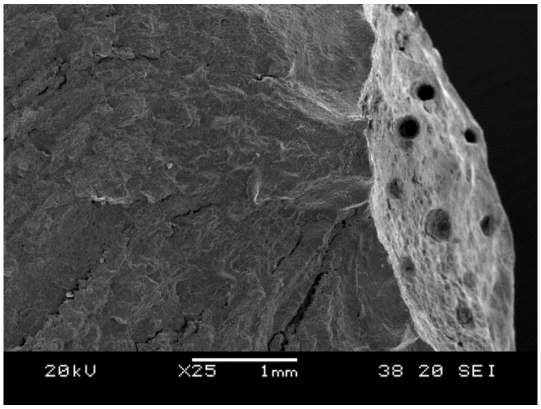

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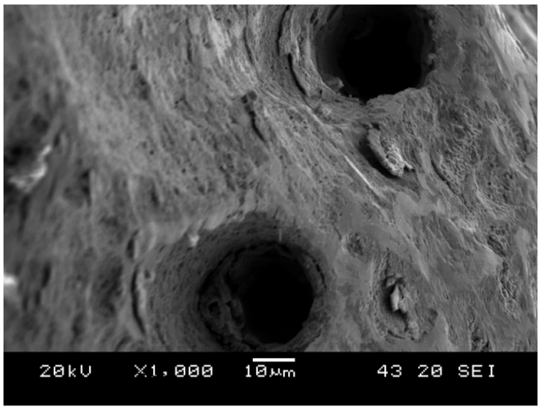

(d)

Figure 8. SEM photos of fractured surface of corroded bars in Fig. 11: (a) and (b) L/D = 5 with 34.20% mas loss, (c) and (d) L/D = 15 with 11.76% mass loss

7 ANALYTICAL MODELLING

Kashani et al. (2015c) have developed a new phenomenological hysteretic model for reinforcing bars that includes the effect of inelastic buckling and low-cycle fatigue degradation. It should be noted that buckling is a second order effect due to the geometrical nonlinearity and large deformation. Unlike the old traditional uniaxial material models for reinforcing bars this advanced material model combines the material nonlinearity due to yielding of steel with geometrical nonlinearity due to buckling and low-cycle fatigue degradation into a single material model. This model has been validated against an extensive set of experimental and numerical simulation data of isolated reinforcing bars (Kashani 2014). However, the fatigue material constants that were used in the model development were not calibrated to include the effect of buckling on fatigue material constants. This has been addressed by Kashani et al. (2015a,b) and summarised in this paper.

A comparison between the improved model using the calibrated fatigue material constants of uncorroded bars and the experimental results has been made and shown in Figure 9.

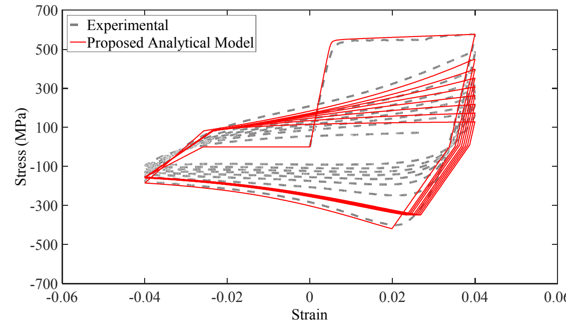

Figure 9. Comparison of the proposed analytical model and the experimental results of a 12mm diameter bar with *L/D* = 15 at 5% strain amplitude

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